National Aeronautics and Space Administration

YEARS 1-3 **EXECUTIVE SUMMARY**

Lunar University Network for Astrophysics Research (LUNAR)

PI: Jack Burns (U. Colorado)

NASA LUNAR SCIENCE INSTITUTE

3.1 EXECUTIVE SUMMARY

The Lunar University Network for Astrophysics Research (LUNAR) is a team of researchers and students at leading universities, NASA centers, and federal research laboratories undertaking investigations aimed at using the Moon as a platform for space science. LUNAR research includes Lunar Interior Physics & Gravitation using Lunar Laser Ranging (LLR), Low Frequency Cosmology and Astrophysics (LFCA), Planetary Science and the Lunar Ionosphere, Radio Heliophysics, and Exploration Science. The LUNAR team is exploring technologies that are likely to have a dual purpose, serving both exploration and science. There is a certain degree of commonality in much of LUNAR's research. Specifically, the technology development for a lunar radio telescope involves elements from LFCA, Heliophysics, Exploration Science, and Planetary Science; similarly the drilling technology developed for LLR applies broadly to both Exploration and Lunar Science.

Lunar Laser Ranging

LUNAR has developed a concept for the next generation of Lunar Laser Ranging (LLR) retroreflector. To date, the use of the Apollo arrays continues to provide state-of-the-art science, showing a lifetime of >40 yrs. This program has determined properties of the lunar interior, discovered the liquid core, which has now been confirmed by seismometry, and most of the best tests of General Relativity (GR). However, the single shot ranging accuracy is now limited by the structure of the Apollo arrays. The next generation LLR program will provide lunar emplacements that will support an improvement in the ranging accuracy, and thus the lunar physics, by factors of 10-100.

> "A new Lunar Laser Ranging (LLR) program, if conducted as a low cost robotic mission or an add-on to a manned mission to the Moon, offers a promising and cost-effective way to test general relativity and other theories of gravity…The installation of new LLR retroreflectors to replace the 40 year old ones might provide such an opportunity". *New Worlds, New Horizons in Astronomy & Astrophysics (NWNH)*

In the near term, the LLR stations that have ranged to the Apollo retroreflectors will see an improvement in accuracy of 3-11 using their existing hardware. More important, the number of returns required to obtain a 1-mm normal point is reduced by a factor of 10-100. This means that as soon as the next generation retroreflectors are deployed, the improvements in the lunar and gravitational physics will begin.

> "Deploying a global, long-lived network of geophysical instruments on the surface of the Moon to understand the nature and evolution of the lunar interior from the crust to the core…to determining the initial composition of the Moon and the Earth-Moon system, understanding early differentiation processes that occurred in the planets of the inner solar system". *Vision and Voyages for Planetary Science in the Decade 2013-2022*

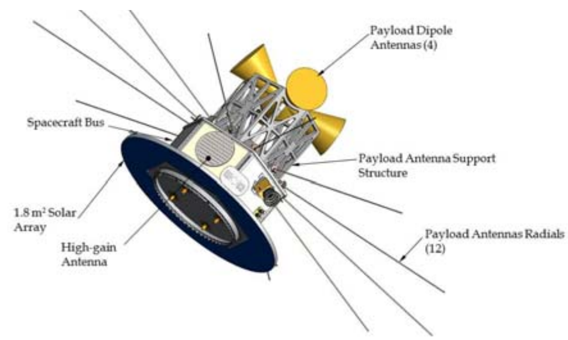
The LUNAR team has shown that the accumulation of dust on the lunar retroreflectors causes a significant loss in the return signal. Because of this, dust-mitigation techniques for use with corner cubes were studied. One such technique is to apply a hydrophobic surface coating. This coating, known as LOTUS, was originally developed to keep surfaces dust-free for missions to the Moon and Mars. The LOTUS coating is being applied to some of the corner cubes and its far-field pattern is being studied to determine the effects of the coating on the corner cube.

Low Frequency Cosmology and Astrophysics (LFCA)

The focus of the LUNAR LFCA research is to strengthen the science case and develop relevant technologies related to tracking the transition of the intergalactic medium (IGM) from a neutral to ionized state during the time that the first stars and first accreting black holes were forming using the redshifted 21-cm signal from neutral hydrogen. The eventual goal is to exploit the "radio-quiet" properties of the Moon's farside as the site for a lunar radio telescope to conduct these fundamental measurements.

> "What were the first objects to light up the Universe and when did they do it?" *NWNH*

The Astronomy and Astrophysics Decadal Survey (*NWNH*) identified "Cosmic Dawn" as one of the three objectives guiding the science program for this decade. In the science program articulated in *NWNH* (Chapter 2), *Cosmic Dawn* was identified as a science frontier discovery area that could provide the opportunity for "transformational comprehension, i.e., discovery." This is one of LUNAR's principal scientific thrusts.



Artist's concept of DARE spacecraft.

LUNAR members have been pioneers in the development of the theory and numerical simulation of the first stars and galaxies, and predictions of sky-averaged spectrum and the spatial structure of the 21-cm signal. Concurrently, LUNAR has developed new technologies and mission concepts to observe the low frequency radio signals from Cosmic Dawn. One exciting advanced concept called DARE (Dark Ages Radio Explorer) will orbit the Moon, take data only above the lunar farside, and will make the first observations of the first stars and galaxies at times <0.5 billion years after the Big Bang. In addition, LUNAR is engaged in technology development specifically to prove new antenna designs capable of being deployed in significant numbers on the lunar surface as an interferometric array. Innovative concepts include roll-out arrays of polyimide (e.g., Kapton) film with embedded metallic dipoles and magnetic helical antennas made of memory metals.

Although the primary focus of a future lunar radio telescope is likely to be Cosmic Dawn, such a telescope would be a powerful instrument for other high priority studies or would be able to conduct other interesting studies by virtue of the Cosmic Dawn observations. Examples include both searches for the magnetospheric emission from extrasolar planets and surveys for radio transients. These respond to recommendations from *NWNH*, which identified both "identification and characterization of nearby habitable exoplanets" and "time domain astronomy" as other science frontier discovery areas.

Planetary Science connection to LFCA

The Scientific Context for the Exploration of the Moon (SCEM) identifies the "Lunar Environment," particularly the fact that the lunar atmosphere presents the nearest example of a surface boundary exosphere, as one of four guiding themes for science-based exploration. From this theme, the report develops a set of science goals, including "Determine the global density, composition, and

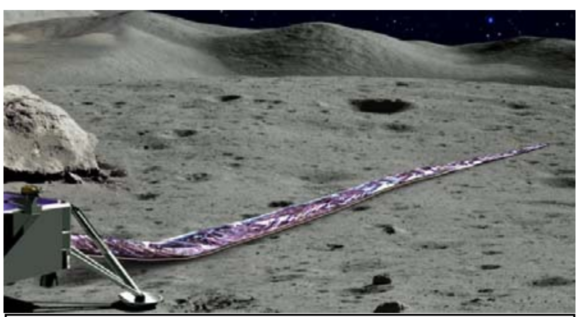
> "Planetary exospheres,…tenuous atmospheres that exist on many planetary bodies, including the Moon, Mercury, asteroids, and some of the satellites of the giant planets, are poorly understood at present. Insight into how they form, evolve, and interact with the space environment would greatly benefit from comparisons of such structures on a diversity of bodies." *Vision & Voyages for Planetary Science in the Decade 2013–2022*

time variability of the fragile lunar atmosphere before it is perturbed by further human activity." The SCEM report also notes that the Moon may continue to outgas and that the lunar atmosphere, as it is coupled to the solar wind, is a dynamic system. As such, long-term monitoring is required to understand its properties. Further, as a surface boundary exosphere, studies of the Moon are likely to inform processes occurring on Mercury, other moons, asteroids, and potentially even Kuiper Belt objects. LUNAR has developed a concept to measure the Moon's ionospheric density using the plasma frequency cutoff from observations with low frequency dipole antennas on the lunar surface.

"The Moon offers a large, stable surface in which to build a large, capable low-frequency radio array for the purpose of imaging solar sources at wavelengths that cannot be observed from the ground, an array that is well beyond the current state of the art for antennas in space." *SCEM*

Radio Heliophysics

High-energy particle acceleration occurs in diverse astrophysical environments including the Sun and other stars, supernovae, black holes, and quasars. A fundamental problem is understanding the mechanisms and sites of this acceleration, in particular the roles of shock waves and magnetic reconnection. Within the inner heliosphere, solar flares and shocks driven by coronal mass ejections (CMEs) are efficient particle accelerators which can be readily studied by remote observations. There remain significant questions to answer about these radio bursts and the acceleration processes that produce them, including where within the CME Type II emission is produced, and how the alignment between the shock surface and the coronal magnetic field changes the acceleration. Electron densities in the outer corona and inner heliosphere yield emission frequencies below ~10 MHz. Observations must be conducted from space because the terrestrial ionosphere is opaque in this frequency range, preventing any of this emission from reaching a receiver on Earth. Work on the *Radio Observatory on the Lunar Surface for Solar Studies (ROLSS)* concept has included refinement of instrument performance requirements, prototyping of critical components such as antennas and correlator electronics, and the use of simulations and observations from analogous instruments in space or radio arrays on Earth.



Artist's concept of a lander with a short length of polyimide film including two deposited dipole antennas (ROLSS prototype).

Since the first space exploration missions, in-situ interplanetary dust detection has been an important issue, both in order to understand the interplanetary and interstellar sources of dust, but also because of the effects that fast-moving dust can have on equipment and humans in space and on the lunar surface. Most dust measurements have been performed with instruments specifically designed to characterize dust particles, but recent work has shown that radio receivers are also able to measure electric signals associated with individual dust grains impacting spacecraft at high speed. Based on this recent work, the LUNAR team realized that the detection and monitoring of interplanetary dust could be a valuable additional science goal for ROLSS and any future far-side low frequency radio arrays. In order to learn more about this technique, and to demonstrate that ROLSS could also make such measurements, the LUNAR team investigated dust-related signals recorded by the S/WAVES radio instrument onboard the two STEREO spacecraft near 1 A.U. during the period 2007-2010.

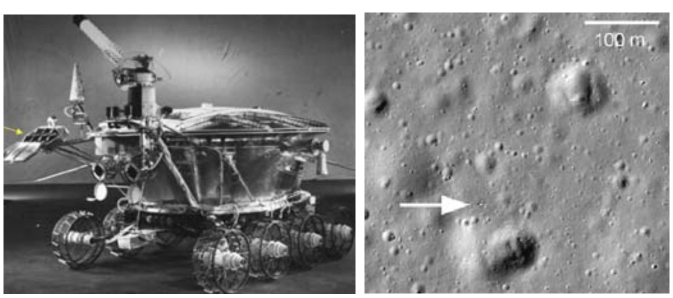
Exploration Science

The LUNAR team is investigating human missions to the lunar L2/Farside point that could be a proving ground for future missions to deep space while also overseeing scientifically important investigations. On an L2 mission, the astronauts would travel 15% farther from Earth than did the Apollo astronauts and spend almost three times longer in deep space. Such missions would validate the Orion Multi-Purpose Crew Vehicle's life support systems for shorter durations, would demonstrate the high-speed reentry capability needed for return from deep space, and would measure astronauts' radiation dose from cosmic rays and solar flares to verify that Orion provides sufficient protection. On such missions, the astronauts could teleoperate landers and rovers, which would obtain samples from the geologically interesting (and unexplored) farside (i.e., South Pole-Aitken Basin) and deploy a lunar radio telescope. Such telerobotic oversight would also demonstrate capability for future, more complex deep space missions.

The LUNAR Simulation Laboratory at U. Colorado has been developed to mimic the temperature and photon radiation environment of the Moon's surface over the course of a full lunar rotation. It has tested science equipment (e.g., polyimide film antennas) and deployment techniques using mini-rovers that are envisioned for both robotic and human exploration of the Moon. It serves as a facility to test other, Exploration-specific technologies, both for the Moon or other airless bodies such as NEOs.

> "The lunar surface offers extraordinarily radio-quiet sites on the lunar farside that could enable a highly sensitive low-frequency radio telescope…An innovative concept recently proposed would have a complete antenna line electrodeposited on a long strip of polyimide film…As a result of the high astronomical priority of this work and the uniquely enabling character of the radio-quiet farside lunar surface, such efforts deserve cultivation." *SCEM*

Automated sensor deployment techniques are needed for surface missions in which instrument packages (either for Exploration or science) should or must be deployed at some distance from a lander. One option for deployment is a rover, but lower mass options, involving spring-and-pulley systems, are also being explored by the LUNAR team. Intended originally for lunar sensors, a spring-and-pulley system may be a useful technology for other low gravity environments.



Left: Lunokhod 1 lander. *Right:* LRO image of Lunokhod 1.

An accurate grid or selenographic coordinate system will be critical in future robotic and/or manned missions. Lunokhod 1 had never been ranged to since the coordinates of the final resting place were not sufficiently accurate. Using the high resolution imagery, LRO identified the location of Lunokhod 1 and these coordinates were given to the LUNAR team for use at the Apache Point Observatory Station. This allowed laser returns to be obtained from Lunokhod 1 for the first time. However, the LLR position of Lunokhod 1 was different from the LRO coordinates by 100 meters. Thus, this new data point should allow a very significant upgrade to the seleodetic coordinate system being used by LRO. Additional retroreflectors will serve to tie down the coordinate system in a variety of new locations.

Drilling in the lunar regolith requires a different approach than used on Earth, as the Apollo astronauts discovered. Such drilling may be required either for stability or thermal control. The LUNAR team, with partner Honeybee Robotics, has been exploring a gas-assisted pneumatic drill, which is demonstrating relatively deep penetrations with limited resource requirements.

Regolith may prove to be an effective construction material. The LUNAR team has been exploring how modest equipment could be used to fuse lunar regolith into a concrete-like material, which could then be used for construction of large structures and astronomical telescope mirrors, without the expense of having to carry most of the material to the surface.

Education & Public Outreach (EPO)

LUNAR has a diverse and aggressive EPO effort aimed at enhancing the awareness and knowledge about the Earth-Moon system. The largest elements involve the creation of a nationally-distributed children's planetarium show and extensive teacher workshops, many in partnership of the *Astronomical Society of the Pacific*. Another key element is support for high school robotics clubs making their own models of a lunar rover capable of deploying a radio telescope on the lunar surface. A final strategy is to take advantage of NASA missions and natural events such as eclipses to increase public awareness of science and of NASA's role.

The children's planetarium program is based on the award-winning book, "Max Goes to the Moon". NASA astronaut Alvin Drew played a role in the development of this show. On his mission to the ISS, he read the story "Max Goes to the Moon" to the children of Earth. Alvin introduces the story in our planetarium show. Using our well-developed process of "formative evaluation", we showed the program to test audiences of school children of the target age and also to hundreds of lunar scientists at the 2011 NLSI workshop. The feedback we gathered resulted in significant improvements to the show. "Max" is now complete and we are beginning distribution of the program.

Our numerous K-12 teacher workshops focused on getting the latest discoveries about the Earth-Moon system and cosmology and the early Universe into the classroom. By holding workshops at the Astronomical Society of the Pacific meeting, we increased the number of teachers reached to much higher numbers than we originally proposed.

We began working with high school robotics clubs to challenge them to build a small rover that could deploy low frequency radio telescopes on the nearside and farside of the Moon. A student from one of these schools was invited to the NLSI Lunar Forum in the summer of 2011 to show his rover to the lunar community.

We planned public events associated with the LCROSS/LRO mission as well as the lunar eclipse in December 2010. The lunar eclipse was the largest public astronomy event in Boulder, CO since the "Deep Impact" comet mission in 2005. Approximately 1500 people crowded into a planetarium that seats 212 (using the lobby, the grounds, and the surrounding university). All heard about NASA's lunar science in addition to seeing the eclipse.